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§1. Qualitative theory and early experiments. When a rod of iron (or other magnetic substance) is rotated about its axis it becomes longitudinally magnetized, and in the direction opposite to that in which it would be magnetized by an electric current flowing around it in the direction of rotation.[1] The magnetization thus produced is not due to the rotation of the rod as a whole, however, but to the rotation of the magnetic elements which are entrained in the motion of the rod. Hence the idea arose that if the rod, at rest, were magnetized transversely, and the magnetization rotated by a two phase electrical system in a plane normal to its axis, longitudinal magnetization should result.

In or about 1921 Dr. Lewi Tonks began an investigation based on this idea, but abandoned it because his apparatus was inadequate for the purpose.[2] The subject was again, a little later, in 1922, and independently, attacked by J. W. Fisher,[3] in London; but the extraneous disturbances were so great that no useful conclusions could be reached. Fisher attacked the problem again, and with much greater success, in 1925,[4] when he obtained null effects with magnetite and iron. These later experiments were made by magnetometer methods, and at frequencies from 2×10^4 to 5×10^4 per second. In the first group, on magnetite in an applied field of about 4 gausses, deflections of 1 mm or less (and in the wrong direction when they occurred) were obtained; while rotation of the rod at the same frequency would have given about 35 cm. In the second group, on magnetite and iron, with applied field strengths of about 100 gausses, deflections of a few mm (and in the wrong direction) were obtained; while rotation at the

[1] S. J. Barnett, Phys. Rev. 6, 1915, p. 239, *et al.*

[2] From information given to the author by Professor A. P. Wills and Dr. Tonks.

[3] J. W. Fisher, *Proc. Phys. Soc. Lond.*, 34, 1922, p. 177.

[4] J. W. Fisher, *Proc. Roy. Soc.* (A), 109, 1925, p. 7.

same frequency, in the case of magnetite, would have given about 13 cm.

As Fisher points out in his paper, the gyrostatic magnetization would not be expected to appear unless the magnetic elements suffer at least a mean rotation when the field and the magnetization vector rotate. He at first expected them to do so, and he planned by his experiments to determine the gyromagnetic ratio much more readily than by experiments on the Barnett effect, in experiments on which high frequencies are not practicable.

§2. ROUGH QUANTITATIVE THEORY ON MOST FAVORABLE ROTATION HYPOTHESIS. Even if rotation of the magnetic elements with the field occurs, however, it can be shown[5] that on the most favorable hypothesis Fisher's experiments could be expected to give only a small fraction of the magnetization produced by rotation of the rod at the same frequency. The most favorable hypothesis assumes that when an element rotates with respect to the rod the torque due to adjacent elements and acting to prevent its alignment with the axis is identical with that which acts when all the elements rotate together, *i. e.* when the whole rod rotates. It is in all probability very much greater.

The order of magnitude of the effect to be expected on the above mentioned most favorable hypothesis can be obtained by the following rough process. Let μ denote the moment of the magnetic element, θ the angle it makes with the axis of the rod, N the number of elements per unit volume of the rod, and I the axial intensity of magnetization (always made initially as nearly zero as practicable). Then

$$I = \Sigma\mu \cos \theta$$

the summation extending over the unit volume.

If now an axial magnetic intensity H_0 is applied to the rod a change δI in I will result such that

$$\delta I = \Sigma\delta\mu \cos \theta = \Sigma\mu \sin \theta(-\delta\theta).$$

Now $-\delta\theta$ is proportional to the torque exserted on the element by H_0. That is

$$-\delta\theta = A\mu H_0 \sin \theta$$

where A is a constant for a particular element and will be assumed identical for all elements. Thus

[5] S. J. Barnett, *Phys. Rev.* 27, 1926, p. 115 (Abstract).

$$\delta I = AH_0\mu^2 \sum_0^\pi \sin^2\theta = AH_0\mu^2 N \cdot 2/3$$

The rotating cross-field produces an intensity of magnetization $I_\perp$ normal to the axis of the rod. For simplicity it will be assumed that this intensity of magnetization is due to N' elements all oriented in its own direction. Then

$$\frac{N'}{N} = \frac{I_\perp}{I_\infty}, \text{ or } N' = N\frac{I_\perp}{I_\infty}$$

where I_∞ is the saturation intensity of magnetization of the material. If now the rotating field entrains with its own frequency (ν) each of the N' elements in each unit of volume, the effect on each will be identical with that of an axial magnetic intensity $H' = 2\pi\rho\nu$ (Barnett effect). An axial intensity of magnetization $\delta I'$ will result such that

$$\delta I' = A'H'\mu^2 \Sigma \sin^2\theta$$

where A' is constant like A. Since $\sin\theta = 1$ for every element involved, this equation may be written

$$\delta I' = A'H'\mu^2 N'.$$

From what precedes it follows immediately that

$$\frac{D}{D_0} = \frac{\delta I'}{\delta I} = \left(\frac{A'}{A}\,\frac{3}{2}\,\frac{I_\perp}{I_\infty}\right)\frac{2\pi\rho\nu}{H_0} = C\,\frac{2\pi\rho\nu}{H_0}$$

where D and D_0 are the deflections of the measuring instrument produced by δI and $\delta I'$.
Thus

$$D/D_0 = C\ 2\pi\rho\nu/H_0, \text{ or } D = CD_0\ 2\ \pi\rho\nu/H_0 = C\alpha \qquad (1)$$

where α is the deflection which would have resulted had the whole rod been rotated with the same frequency ν.

If the length of the rod is great in comparison with the diameter, it is easy to show that the cross-magnetization $I_\perp$ is given to a close approximation by the equation

$$I_\perp = \left(\frac{\mu - 1}{\mu + 1}\right)\frac{H_e}{2\pi}$$

where μ is the permeability of the rod and H_e is the field intensity when the rod is removed. When the permeability is far greater than

unity, as in all the experiments with which we are concerned here, it is sufficient to replace the above equation with the following:

$$I_{\perp} = \frac{H_e}{2\pi}.$$

Thus we have for C, with all sufficient exactness,

$$C = \left(\frac{A'}{A}\right)\frac{3}{2}\frac{H_e}{2\pi I_{\infty}}. \quad (2)$$

Even when A'/A is put equal to 1, its maximum possible value, *and one far beyond its probable actual value*, C is always a small quantity, so that the value of D to be expected is much less than α.

In Fisher's first experiments on magnetite powder, in which the deflections D (always in the wrong direction and doubtless due to accidental and systematic errors) obtained were less than 1 mm. and calculation makes α about 35 cm., C was only about 1/400 with A'/A put equal to unity; so that on the most favorable hypothesis deflections as great as 1 mm should hardly be expected. In the last experiments with solid magnetite, in which D was a few mm. (again in the wrong direction) and calculation makes α about 13 cm., $I_{\perp}/I_{\infty}$ was estimated to be about 1/20, making $C = 1/13$. Hence the above hypothesis calls for deflections of the order of 1 cm. only. Experiments on iron powder also gave results of the same character.

§3. Early experiments by the author. When Fisher's second paper appeared I had under way an investigation of the same effect

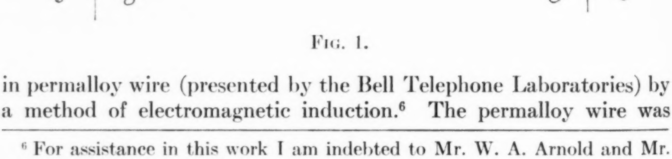

Fig. 1.

in permalloy wire (presented by the Bell Telephone Laboratories) by a method of electromagnetic induction.[6] The permalloy wire was

[6] For assistance in this work I am indebted to Mr. W. A. Arnold and Mr. J. S. Campbell.

formed into a toroid (Fig. 1) with a mean diameter of about 2 ft. and a circular cross-section with diameter about 2 in. After being annealed it was wound with tape and with narrow single layer circular test coils A, B, suitable for measuring the radial flux across its section, and also the flux across a section normal to the axis of symmetry. Another single layer coil C in the form of a close helix was wound over the whole length of the toroid; and over this, a continuous set of coils D of a great many turns, not shown in the figure, to make possible the measurement of minute changes of flux around the ring. The coil system D was connected with a ballistic galvanometer. The toroid with its coils was mounted in the annular space within two sets, 1–4 and 5–8, of parallel and coaxial circular coils, each set consisting of four coils. The mean diameter of each set was equal to that of the permalloy toroid. This toroid was coaxial with the coils, which were so placed that one set produced an approximately uniform radial field in the region occupied by the toroid, the other an approximately uniform field parallel to the axis of the toroid. The best arrangement had to be found by trial, and is illustrated in the figure. The whole system was placed in a toroidal vessel filled with molten beeswax and rosin, which, when it had cooled, held all parts solidly together. The solid system, looking somewhat like a huge doughnut, was then removed from the vessel and mounted on a wooden support with its axis in the direction of the earth's magnetic field.

The two sets of coils were connected to a two phase electrical system with a frequency of 50 cycles per second, which produced a rotary field throughout the permalloy ring, tending (according to the above theory) to magnetize it gyrostatically in one direction or the other around the ring according to the direction of rotation of the field. Calibration of the apparatus showed that it was sensitive enough to measure the effect calculated above (on the hypothesis $A = A'$); but the extraneous disturbances (largely due to heat) were so great as to mask completely any effect of this magnitude, and the investigation was temporarily abandoned.

The toroidal arrangement was adopted in order to eliminate the effect of fluctuations of the earth's magnetic field, and to avoid end effects and thus to take full advantage of the great permeability of permalloy.

§4. New experiments. General method. It has always seemed to me practicable to go much beyond either of these investigations, and I have recently completed a piece of work which does so. The

method used in the work just described is closely related to that of the first work on magnetization by rotation;[7] while the method used in Fisher's later work is closely related to that of the later work on mag-

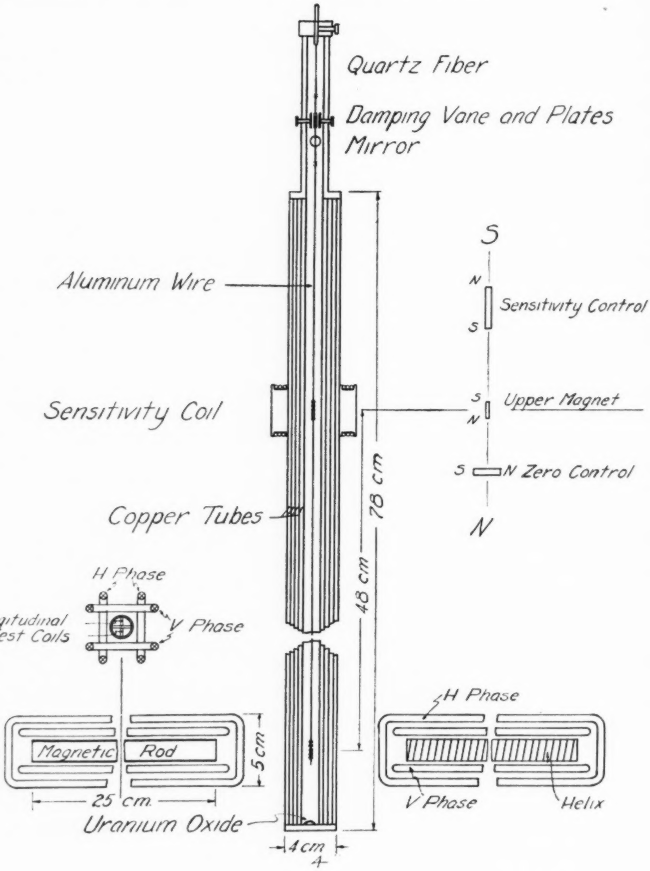

FIG. 2.

[7] S. J. Barnett, *l. c.* in § 1.

netization by rotation[8]—viz., a magnetometer method. A magnetometer method has been used in the new work in preference to an electromagnetic induction method because it is possible with it to use smaller samples of magnetic material, to use higher frequencies, and to attain greater sensitiveness.

In the new work,[9] two similar round rods of the material to be studied (Fig. 2) were mounted with their axes horizontal and normal to the magnetic meridian. Half way between the centers of the rods, and in the same horizontal plane, was the lower magnetic system of an astatic magnetometer. The rods were placed usually east and west of the magnetometer (axial arrangement, Fig. 2) with their axes in the same straight line; but in some of the work they were placed north and south, with the line between their centers in the magnetic meridian (equatorial arrangement). Suitable test coils were wound upon the rods, and suitable magnetizing coils were provided to produce equal horizontal and vertical field intensities when supplied with high frequency currents from a two phase vacuum tube converter. Magnetometer deflections due to the reversal of the direction of rotation were obtained, and all measurements were made which were needed for the calculation of the quantities α and I_1/I_∞.

§5. THE MAGNETIC RODS AND THE TEST COILS. In the early part of the work, in default of better material, rods were built up of the finest iron wire obtainable here (0.007 inch diameter); but they were discarded because the eddy currents were too great. They were replaced with rods built up from small discs of compressed permalloy dust and iron dust, presented by the Bell Telephone Laboratories. From the rings supplied, flat discs 9/16 inch in diameter were cut out and packed closely, with cement between them, in bakelite tubes 5/8 inch external diameter and 1/32 inch thick, and squeezed together in a vise. The rods thus formed were about 25 cm. long. Over each bakelite tube three test coils were closely wound, viz., two ten-turn longitudinal coils at right angles to each other, and, over them for nearly the whole length of the tube, a helix—all of silk enamel copper wire No. 32. The whole system, with suitable leads, was then mounted in bakelite end rings, and inserted in a much longer bakelite tube of greater diameter, by which the whole could be easily handled and

[8] See especially S. J. Barnett and L. J. H. Barnett, *Proc. Amer. Acad. of Arts and Sciences* 60, No. 2, 1925, pp. 125–216.

[9] S. J. Barnett, *Phys. Rev.* 43, 1933, p. 384 (Abstract). The predicted numbers quoted should be divided by 2.

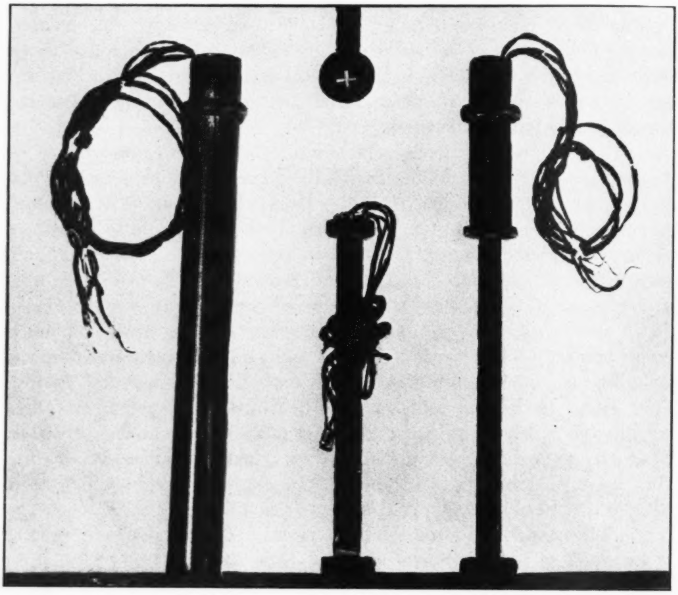

FIG. 3.

adjusted with reference to the magnetometer and magnetizing coils. Exactly similar coils were wound on bakelite rods provided with suitable holders for placing them exactly in the positions alternatively occupied by the coils on the magnetic rods. The arrangements are illustrated in Fig. 3 and Fig. 4.

The permeabilities of the iron and permalloy dust are about 35 and 75, respectively, in weak fields, and their saturation intensities of magnetization about 0.9 those of the solid materials.

§6. THE MAGNETIZING COILS. The magnetizing coils (Fig. 2) were wound in two groups, one to surround each rod or set of test coils. Each group consisted of two pairs, one pair (H coil) designed to produce an approximately uniform horizontal intensity in the region to be occupied by the rod; the other (V coil) a similar and equal vertical intensity. The approximate dimensions are indicated in Fig. 2. Each coil contained 2 x 100 turns of No. 32 silk enamel copper wire.

The mean width of each coil was about 4.0 cm., and the mean distance between the two halves of each coil about 2.2 cm. The coils of each group were wound between hardwood supports on a bakelite tube whose internal diameter was just larger than the external diameter of the rod-holders, and all were properly taped in place and provided with suitable leads. Each group was mounted horizontal in a wooden frame, which was attached by wax to a heavy marble slab mounted on a heavy wooden table under the magnetometer. See Fig. 4. The copper tubes forming the greater part of the magnetometer case (§7) extended downward through a hole in the marble slab. The two pairs of H coils were connected in series, and likewise the two pairs of V coils. To equalize the circuits, the longer coils in one group were made H coils, the longer coils in the other group, V coils. (One group should be turned through a right angle in the figure.)

§7. THE MAGNETOMETER AND ITS CONTROLS. The magnetometer is a modification of the one used in the later work on magnetization by rotation, and is illustrated in Fig. 2. Each system of the astatic pair was built of 11 magnets similar to those used earlier. An extra length of aluminum rod was inserted between the upper system and the mirror in order to make possible better protection of the moving parts from the high frequency magnetic field. For this purpose five coaxial copper tubes, each 1/16 inch thick, coaxial with the suspension and long enough to project well beyond the magnets, were made to replace the lower part of the former magnetometer case. A small piece of uranium nitrate at the bottom of the inclosed space prevented difficulties from electrification of the suspended system.

A small Helmholtz coil centered on the upper magnet made it possible at any time to determine the sensitivity of the instrument.

The sensitiveness and zero were adjusted with great facility by the control system used in earlier investigations.[10] Two small magnets, or groups of magnets, acting chiefly on the upper system, are used. One of them, with its axis parallel to that of this system, alters the sensitivity by motion toward or from the system without changing (much) the zero; the other, with its axis normal to that of the system, alters the zero by motion to or from the system without changing

[10] See S. J. Barnett, *A sine galvanometer for determining in absolute measure the horizontal intensity of the earth's magnetic field. Researches of the Department of Terrestrial Magnetism*, Carnegie Institution of Washington, Vol. 4, 1921, pp. 373–394 (See p. 388). Also, S. J. Barnett and L. J. H. Barnett, *Proc. Amer. Acad. of Arts and Sciences*, Vol. 60, No. 2, 1925.

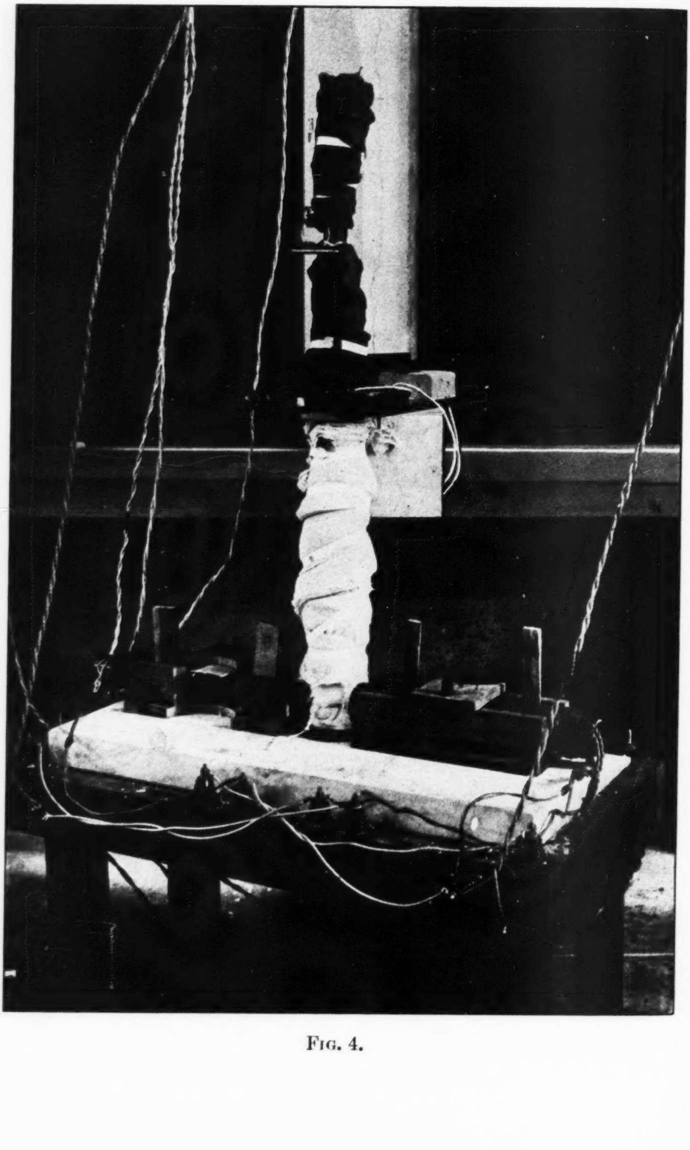

Fig. 4.

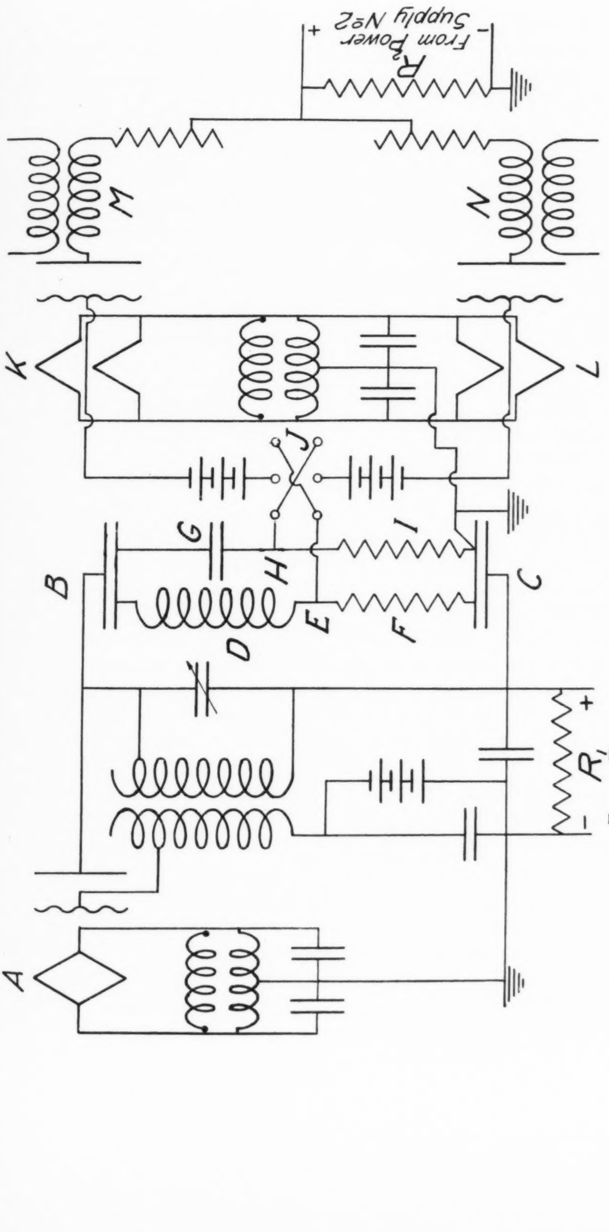
A
B
C
D
E
F
G
H
I
J
K
L
M
N
R_1
From Power Supply No 1
R_2
From Power Supply No 2

FIG. 5.

(much) the sensitivity. Gross adjustment by slides and fine adjustment by micrometers are provided. (Electric coils with adjustable currents can of course replace the magnets, and have sometimes been used, but not in this investigation.) The difficulty of this investigation, as well as that on magnetization by rotation, would have been greatly increased without this method of controlling the magnetometer.

The magnetometer, with its controls, was mounted in brass supports on the end of a heavy beam of marble bolted to and projecting out from a heavy concrete shelf supported by the floor and wall of the laboratory.[11]

In order to screen the magnetometer thermally and to prevent the formation of convection currents the magnetometer was covered almost completely with a thick coat of felt and other insulating material. See Fig. 4.

§8. THE POWER SUPPLY. Single phase power was obtained from the mains of the local transmission system at 50 cycles per second, and transformed by a vacuum tube system for use at the higher frequencies needed in two phases in quadrature. See Fig. 5.

A tuned-plate vacuum tube oscillator A[12] produces a voltage of constant frequency and of approximately sine form between the terminals B and C. Through two condensers this voltage is impressed on the two partial circuits DEF and GHI in parallel. D has inductance, but only negligible capacity and resistance; G, capacity, with negligible inductance and resistance; and F and I, resistance without appreciable capacity or inductance. The resistance of F is made equal to the reactance of D, and the resistance of I equal to the reactance of G. With these adjustments made, the voltages along F and I, whose lower ends are connected together, are in quadrature. Through a switch J, and biasing batteries, one of these voltages is impressed between the grids and filaments of a pair of 50 watt tubes K in parallel; the other, between grids and filaments of a similar pair L.[13] All these filaments are in parallel and supplied by the same filament transformer, the center of whose secondary is connected to the junction between F and I.

[11] For assistance in mounting the magnetometer and the magnetizing coils I am indebted to Dr. Otto Beeck.

[12] For advice with regard to this part of the apparatus I am indebted to my colleague Professor S. S. Mackeown.

[13] This arrangement was used in the latter part of the work, a single battery having been connected between the junction of F and I and all the filaments in parallel in most of the work.

The power for the oscillator was furnished by an AC-DC full-wave vacuum tube converter with three-stage filter, the power for the 50 watt tubes by a similar converter of much larger capacity. The condensers and chokes were so large as to make very constant terminal voltages certain.

The positive terminal of the larger converter was connected through adjustable resistors and the primaries of two Western Electric high frequency transformers M and L to the plates of the two pairs of 50 watt tubes, the negative terminal to the center-tap of the filament transformer.

The secondaries of the transformers M and L were connected separately (Fig. 6) through reversing switches and similar adjustable

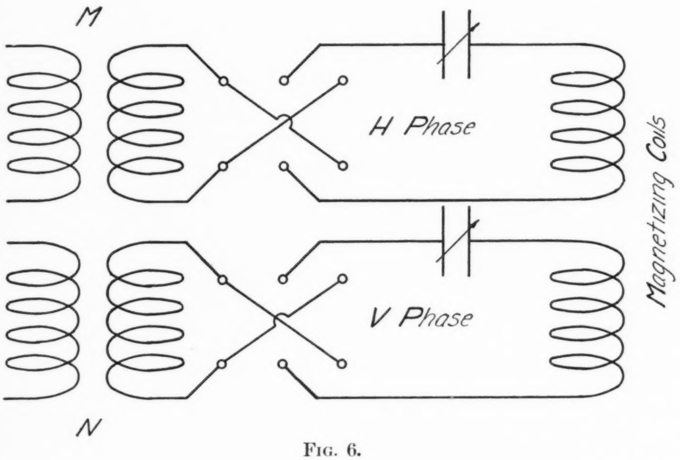

FIG. 6.

condensers to the terminals of the magnetizing coils. By means of the condensers the two secondary circuits were tuned sharply to the oscillator frequency. In this way equal harmonic currents in quadrature were made to traverse the two sets of magnetizing coils, designated as H-phase and V-phase coils. By means of switches not shown in the figure a Weston thermo-ammeter could be thrown into either secondary at will, and a D. C. Weston ammeter into either of the plate circuits. Also, switches made it possible to exchange at will the transformer coils in the secondary circuits.

§9. THE FIELD PRODUCED BY THE MAGNETIZING COILS. To study this, one of the longitudinal test coils wound on its bakelite support was inserted in the position normally occupied by a magnetic rod in one of the groups of magnetizing coils, and turned about until it was parallel to the turns of one of the pairs of magnetizing coils. Then the flux through the test coil, and hence the mean magnetic intensity, were determined by the common ballistic method for a measured current in the magnetizing coil. This was repeated with the other longitudinal test coil and the other magnetizing coil of the group; then the whole process was repeated for the other group. The resulting values of the mean magnetic intensity per unit current were, as would be expected, nearly the same, the mean being about 30 gausses per ampère.

With the currents ordinarily used in most of the high frequency work, this makes the intensity of the rotating field about 15 gausses.

§10. TESTS FOR ABSENCE OF EDDY CURRENTS. The principal tests were made in two parts: (1) One of the longitudinal test coils was inserted in the proper position and turned about until it was parallel with the turns of one of the magnetizing coil pairs, as in §9. With a ballistic galvanometer in the test coil circuit, the mean throw D_B was determined when a known steady current was reversed in the magnetizing coil. The process, with the same current, was then repeated with a longitudinal test coil on one of the magnetic rods replacing the coil on bakelite, the mean throw D_M being determined; and the whole process was repeated for each of the materials to be studied. For each substance the ratio D_M/D_B was determined. (2) Instead of the steady direct current, a steady high-frequency current was passed through the magnetizing coils, and the electromotive forces E_M and E_B in the longitudinal test coil measured, both for the magnetic material and for the bakelite. For each of the magnetic materials the ratio E_M/E_B was calculated.

At the frequency 14650 cycles per second, E_M/E_B was found equal, or very nearly equal, to D_M/D_B, showing that no eddy currents of any consequence existed.

At the frequency 21000 cycles per second, E_M/E_B was somewhat less than D_M/D_B in the case of the permalloy, with which alone this frequency was used.

The practical absence of eddy currents at the lower frequency also follows from the fact that the currents in the magnetizing coils (the secondary circuits being tuned) were practically identical whether the

magnetic rods were in their holders within the magnetizing coils, or were removed.

§11. Tests for the direction of rotation of the field. For every arrangement used the direction of rotation was directly determined by means of a small washer of brass or small aluminum ring carried by fine threads or bundles of silk fibres and inserted in the region within the field coils. There was thus never any uncertainty in this matter.

§12. Quadrature of the two phases. As stated above, the two phases must be in quadrature if the impedances D and F, Fig. 5, are equal, and the impedances G and I equal. Tests for these equalities were made by interchanging D and F, and by interchanging G and I. When the interchanges produce no alterations in the secondary currents of the appropriate phases, the impedances in each branch are equal and the secondary currents in quadrature.

Another test is to measure the electromotive force induced in one of the longitudinal test coils wound on the magnetic rod as the rod and coil are turned about the horizontal axis. If the electromotive force remains constant the currents are in quadrature.

Both these tests were made (but not usually at the same time) in this work and the currents were always found to be in, or nearly in, quadrature.

§13. Elimination of error due to residual magnetization. Inasmuch as it is never possible to obtain exactly identical currents in the magnetizing coils for the two directions of rotation, and as residual magnetization—a function of eddy currents and temperature—is always present to a greater or less degree, it was necessary to eliminate possible error from this source. This was done simply by interchanging the two rods and reversing their directions. The mean result is independent of the error. As a matter of fact, however, the error vanished in this work, even in the case of the iron dust, which could not be demagnetized by any means so well as the permalloy dust.

§14. Elimination of errors due to leakage between primary and secondary circuits. If there is leakage between the circuits of one of the phases, let us say the H-phase for definiteness, and if the field of the H coils through asymmetry has a component normal to the magnetometer magnet or along the magnetic rods, then, if we close the V switch *on the right* (for definiteness) and *reverse the H switch*, the magnetometer deflection D' will be the sum $D_R + D_L$ of two parts, one (D_R) due to the effect of rotation being looked for (if

any), and one (D_L) due to the leakage. If now we set the V switch *on the left*, and then reverse the H switch *in the opposite direction*, the deflection D'' will clearly be equal to $D_R - D_L$. Thus the mean of D' and D'' will be equal to D_R. In making the observations quoted here this procedure was always applied to both phases, although no appreciable effect of leakage was manifest with the permalloy rods, or with rods absent. In every set, equal numbers of observation were made for each of the cases: (1) H-switch left, V-switch reversed right to left and left to right; (2) H-switch right, V-switch reversed right to left and left to right; (3) V-switch left, H-switch reversed right to left and left to right; (4) V-switch right, H-switch reversed right to left and left to right. The mean double deflection for (1), (2), (3), and (4), proper attention being paid to directions of reversal, was thus independent of leakage in either secondary.

§15. THE AXIAL AND EQUATORIAL ARRANGEMENTS. In all the final work with the magnetometer in the axial position the ends of the rods were about 7 cm. from the magnetometer axis; while in that with the equatorial position the axes of the rods were about 9 cm. from this axis.

§16. THE ABSOLUTE AND ROD SENSITIVITIES AND COILS. The small coils in the Helmholtz pair centered on the upper magnetometer magnet (Fig. 2) each had 3 turns with mean diameter 2.9 cm. and were at the mean distance apart of 3.45 cm. Their constant was thus 0.69 gauss per ampère. Reversal of a current 1.55 volt/80,000 ohms through these coils ordinarily gave a deflection, A_0, of about 12 cm. or more. This 12 cm. deflection corresponds to a deflection of 1 mm. for 1.1×10^{-7} gauss. The deflection A_0 obtained in this way will be referred to as the *absolute sensitivity*.

The helices wound longitudinally over the rods had about 710 turns in 23.2 cm. The reversal of a current 1.55 volt/180,000 ohms through the helices on both rods in series produced a double deflection R_0 which will be referred to as the *rod sensitivity*.

The magnetic intensity at the center of a rod impressed by the current mentioned in the helices is approximately $H_0 = 3.3 \times 10^{-4}$ gauss. In the work described here R_0 ranged from about 18 cm. to about 37 cm.

If the two helices wound on bakelite are made to replace the helices wound on the magnetic material, the reversal of the same helix current produces a double deflection B_0, which, for the same value of A_0, is of course much smaller than R_0.

For the experiments described here the mean values of R_0 for iron dust at the lower frequency, permalloy dust at the lower frequency, and permalloy dust at the higher frequency were 20.9 cm., 31.4 cm., and 33.1 cm., respectively. For the values of A_0 corresponding to these values of R_0, the mean values of B_0 were 1.5 cm., 1.4 cm., and 1.4 cm., respectively. Thus the corresponding mean values of D_0 were 19.4 cm., 30.0 cm., and 31.7 cm., respectively.

§17. Procedure in making a set of observations. A complete set of observations, aside from the currents in the magnetizing coils, which were read at proper times, comprised the following determinations, which were made in the order indicated: (I) Absolute sensitivity A_0 (7 scale readings) with magnetic rods removed; (II) double deflections D due to reversal of H-switch from right to left and left to right (3 groups of 11 scale readings each) with V-switch on left, and deflections due to reversal of V-switch from right to left and left to right (3 groups of 11 scale readings each), with H-switch on the left, the two sets of groups being "sandwiched"; (III) repetition of (I), but with the magnetic rods in place; (IV) rod sensitivity R_0 (7 scale readings); (V) repetition of (II), but with the rods in place; (VI) repetition of (V), but with the roles of the V and H switches interchanged; (VII) repetition (IV); (VIII) repetition of (III); (IX) repetition of (II) (rods removed), but with the roles of the V and H switches interchanged; (X) repetition of (I). All observations were made on a time schedule, the mean times for right and left readings in each group being identical. Between (II) and (III), between (V) and (VI), and again between (VIII) and (IX), the magnetizing coils and rods (when present) were cooled by a fan motor. A complete set of observations required over five hours to complete.

§18. Summary for one set of observations. As an example, the observations on permalloy for November 6, 1932, are summarized here. The Roman numerals refer to the groups of §17, the Arabic numerals designate the order of the sub-groups. Only the mean result for each sub-group is given.

Rods removed (Air)

I. $A_{0A} = 21.76$ cm.
Mean value of current = 315 m. a.
X. $A_{0A} = 20.77$

Mean $A_{0A} = 21.27$

	V-Switch L		H-Switch L	
II. $D_A =$	$-$ 0.16 cm.	(1)	$+$ 0.36 cm.	(2)
	$+$ 0.04	(3)	$-$ 0.04	(4)
	$+$ 0.15	(5)	$-$ 0.11	(6)
Mean	$+$ 0.01		$+$ 0.07	

Mean $+$ 0.04

	V-Switch R		H-Switch R	
IX. $D_A =$	$+$ 0.18 cm.	(1)	$-$ 0.33 cm.	(2)
	$-$ 0.07	(3)	$+$ 0.07	(4)
	$+$ 0.05	(5)	$-$ 0.13	(6)
Mean	$+$ 0.05		$-$ 0.13	

Mean $-$ 0.04

Mean D_A = 0.00 cm.

Rods in Place

III. A_{0M} = 13.98 cm.	IV. R_0 = 27.77 cm.
VIII. A_{0M} = 15.01	VII. R_0 = 28.98
Mean A_{0M} = 14.50	Mean R_0 = 28.38

	V-Switch L		H-Switch L	
V. $D_M =$	$-$ 0.04 cm.	(1)	$+$ 0.02 cm.	(2)
	$+$ 0.10	(3)	$-$ 0.03	(4)
	$-$ 0.14	(5)	$+$ 0.26	(6)
Mean	$-$ 0.03		$+$ 0.09	

Mean $+$ 0.03

VI. $D_M =$	$-$ 0.11 cm.	(1)	$-$ 0.17 cm.	(2)
	$-$ 0.14	(3)	$-$ 0.05	(4)
	$-$ 0.17	(5)	$-$ 0.04	(6)
Mean	$-$ 0.14		$-$ 0.09	

Mean $-$ 0.11

Mean D_M for Permalloy $-$ 0.04 cm.

It happens in this case that the mean deflection D_A for air is 0.00. Had this not been the case, the procedure would have been to multiply D_A by the ratio A_{0M}/A_{0A} and to substract this from D_M to get the effect on the permalloy alone.

The mean deflection for permalloy is *negative;* whereas in this case a positive deflection, if any, should have occurred according to the theory.

The magnetometer was in the equatorial position.

§19. SUMMARY OF RESULTS FOR IRON DUST. Eight complete sets of observations were made upon iron. The mean deflections D, in cm., classified according to type of reversal, are as follows: (VL) − 0.075; (HL) + 0.264; (VR) + 0.051; (HR) − 0.245, mean of all 0.00. Here VL means that the V-phase switch was set on the left, and the H-phase switch reversed; HR, that the H-phase switch was set on the right, and the V-switch reversed, etc. The positive sign means a deflection in the direction predicted by theory; the negative sign, one in the opposite direction. The results show a decided leakage effect, eliminated from the mean.

For the eight sets the mean deflections and errors (leakage eliminated) are as follows: Air alone, + 0.01 ± 0.02; iron alone, 0.00 ± 0.03; iron—air, − 0.01 ± 0.03.

Five sets were made with the rods turned in one direction, three with the rods interchanged and reversed. The two groups give − 0.02 ± 0.04 and + 0.01 ± 0.01, respectively.

The mean value of the currents was 337 m. a., and the mean value of R_0, 20.9 cm.

§20. SUMMARY OF RESULTS FOR PERMALLOY DUST. At the lower frequency, about 14,650/sec., fourteen complete sets of observations were made on permalloy. With the conventions adopted in §19, the mean deflections classified according to type of reversal are (VL) + 0.07 ± 0.10; (HL) − 0.03 ± 0.12; (VR) − 0.05 ± 0.12; (HR) 0.00 ± 0.07. The corresponding observations on air give (VL) − 0.00 ± 0.04; (HL) + 0.01 ± 0.05; (VR) + 0.04 ± 0.06; (HR) − 0.02 ± 0.07. Here the effect of leakage, if existent, is very small.

For the fourteen sets the mean deflections and errors (leakage eliminated from each set) are as follows: Air alone + 0.03 ± 0.07; permalloy alone, − 0.01 ± 0.13; permalloy—air, − 0.04 ± 0.14.

The mean value of the current was 352 m. a. and the mean value of R_0, 31.4 cm.

Three sets were obtained at the frequency 21,000, giving the mean deflection + 0.03 ± 0.02. The mean value of R_0 was 33.1 cm., and the mean value of the current 171 m. a.

§21. CALCULATION OF MAXIMUM DEFLECTIONS TO BE EXPECTED ON ROTATION HYPOTHESIS. From (1) to (2), §2, we have, when A'/A is put equal to unity,

$$D = \frac{3}{2} \cdot \frac{\rho\nu}{I_\infty} \cdot \frac{H_e}{H_0} \cdot D_0. \tag{1}$$

For compressed iron dust and permalloy dust, whose densities are about nine-tenths those of the homogeneous metals, we may take the saturation intensities of magnetization (I_∞) as about 1550 and 1550 x 11/21, respectively.

For permalloy at the lower frequency the mean value of H_e was about 30 x 1.41 x 0.35 gauss (§§9, 20), the rms. value of the current having been read by the ammeters. The values of D_0 and H_0 were 30.0 cm. and 3.3 x 10^{-4} gauss (§16). The lower frequency was about 14,650 per second, and ρ may be taken as m/e x 1.05 e.m. units, or 1.05 x 0.57 x 10^{-7} e.m.u. Hence, by substitution in (1), we obtain D = 2.1 cm. In the same way, for iron at the lower frequency, we obtain D = 0.7 cm.; and for permalloy at the higher frequency, 21,000 per second, we obtain D = 1.5 cm. The last value should be reduced somewhat because eddy currents were appreciable. All the values are slightly too high because the two phases were not, in general, in perfect quadrature.

As the results show, the deflections actually obtained were in all cases far smaller than the values of D calculated above on the most favorable hypothesis.

§22. Further discussion of results. When the magnetization vector rotates, as in these experiments, the conditions are far more complicated than when a rod itself rotates, and it is impossible to give any detailed theory of what happens if the elements themselves rotate. The results of the experiments, together with discussions of the subject with others, especially Professor Einstein and Professor Epstein, have convinced me that any rotation of the elements which could possibly occur would be accompanied by changes of magnetization much less than the minimum detectable in this work ($A' << A$ in §2) and that the most probable interpretation of the null effect is, as Professor Einstein suggested two years ago, that the elements do not rotate with the field at all, but have their moments periodically *reversed* by the rotating field.

Thus, for simplicity, we may imagine half the elements to have moments with vertical and axial components only, and half to have moments with horizontal and axial components only. The alternating vertical intensity will then change the vertical cross magnetization by reversing moments of the first group, and the alternating horizontal intensity will change the horizontal cross magnetization by reversing

moments of the second group. Thus the magnetization vector will rotate without any rotation of the elements, and thus without the production of any longitudinal magnetization by a gyromagnetic process.

There have long been other indications favoring the hypothesis that in the early part of the magnetizing process (weak fields) the magnetization proceeds by such quantum jumps, or reversals, of the elements, and not by changes in their orientation; and the work described here, which has to do with weak fields only, strongly supports the other evidence. In strong fields, however, the indications are that changes of magnetization are due to gradual changes in the orientation of the elements. If this is the case, a repetition of the investigation described here, but with fields strong enough nearly to saturate the magnetic material, should yield positive results instead of a null effect. But there are obviously great difficulties in the way of such an investigation. Professor Einstein has suggested to me an equivalent investigation in which it is hoped that the difficulties will be less, and work on this has been started.

§23. FURTHER ACKNOWLEDGMENTS. I am under many obligations for help in addition to those mentioned in what precedes. The Board of Research of the University of California, and the California Institute of Technology, have given generous support to the work. Special mention must be made also of the Carnegie Institution of Washington and the National Research Council for indispensable equipment; of Dr. Arnold, Dr. Buckley, and the Bell Telephone Laboratories for materials, equipment, and information of great importance; of Dr. Vaino Hoover, who, as research assistant, has given me very valuable help in the recent part of the investigation; and of the instrument-makers of the University, and the Institute, whose work has been excellent. The experiments have been conducted in the Norman Bridge Laboratory of Physics of the Institute.

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